Journal of Cleaner Production 191 (2018) 40–47

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Brassica carinata-derived biodiesel production: economics, sustainability and policies. The Italian case

Marcello Basili*, Maria Alessandra Rossi

Department of Economics and Statistics, University of Siena, Piazza San Francesco 7, 53100 Siena, Italy

ARTICLE INFO

Article history:
Received 11 November 2017
Received in revised form
21 March 2018
Accepted 30 March 2018
Available online 20 April 2018

Keywords:
Brassica carinata
Second-generation biodiesel production
Land use change
Sustainability
Climate change

ABSTRACT

The paper explores the economic feasibility and environmental sustainability of producing second-generation biofuel in Italy from *Brassica carinata,* a non-edible flowering plant of the *Brassicaceae* family, in a context of rotation with wheat (and eventually other crops). The framework considered allows to rule out issues of ILUC and is highly relevant in a country where extensive monoculture is extremely widespread and there is a high degree of dependence on foreign imports for both biofuels and biofuels-related raw materials, especially from countries such as Indonesia, where the adverse impacts of first-generation biofuel production on the environment are most felt. Using yield and cost data from 5 experimental fields in Italy and taking into account potential returns from the sale of biodiesel and its by-products, glycerine and expeller/meal, the economic sustainability of the entire biodiesel production chain (cultivation, oil extraction and oil refining) is established. Implementation of the Argonne National Laboratory's GREET life cycle model, suitably adjusted so as to apply it to the BC case, confirms also a high environmental sustainability. The range of positive economic effects and externalities that may be triggered by the development of a BC-derived biofuel production chain justifies some form of policy intervention.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

Greenhouse gases (GHGs), such as CO_2, are gases contributing to the greenhouse effect causing climate change. In the EU, transport is the second biggest GHGs emitting sector after energy, with 22.2% of the total in 2013. Thus, biofuels are among the possible green answers to the increasing level of CO_2 emissions in the atmosphere. The *EU Energy and Climate Change Package* (2009/147) recognizes this, establishing that, by 2020, EU Member States have to reach a minimum of 10% of renewable energy consumed in transport. The Renewable Energy Directive (RED, 2009/28/EC) sets the sustainability requirements for biofuels to count towards the 10% goal.

The latter include reaching a minimum GHGs emissions-saving threshold (initially set at 35%, to increase to 50% and then to 60% in 2018), not being produced from: feedstock grown on land with high biodiversity value such as primary forests and highly biodiverse grasslands; lands with high-carbon-stocks such as wetlands or continuously forested areas; and peat land. In addition, the Directive states that biofuels produced from waste, residues, non-food cellulosic and lignocellulosic material count for double their value for the purpose of calculating the target for renewable energy in transport (so-called double counting).

The lively debate that has accompanied and followed the adoption of these policy measures has highlighted a number of controversial aspects of biofuel production and consumption: impact on the rise of food prices, high costs, limited contribution to the reduction of greenhouse gases and adverse effects in terms of land-use change (see, e.g., Harris et al., 2015). As a consequence of this debate, in 2015 the European Parliament approved a 7% cap on first-generation biofuels from crops grown on agricultural land (biodiesel and bioethanol obtained from crops also exploited for food production) that can count towards the 10% goal in transportation final energy consumption by 2020.

More recently, in the context of the legislative process leading to the update of the Renewable Energy Directive (so-called “RED II”), introducing an increased binding target for renewable energy consumed in transport, crop-based biofuels have become the object of even greater controversy. Indeed, the EU Commission's initial proposal foresees the progressive phasing out of conventional crop-based biofuels such as ethanol, with a reduction of the 7% cap to

* Corresponding author.
E-mail addresses: marcello.basili@unisi.it (M. Basili), alessandra.rossi@unisi.it (M.A. Rossi).

https://doi.org/10.1016/j.jclepro.2018.03.306
0959-6526/© 2018 Elsevier Ltd. All rights reserved.

3.8% by 2030. If accepted, the proposal would increase reliance on second-generation biofuels, produced from lignocellulosic material, waste or crops not intended for food production, and third-generation biofuels, obtained from algae and microalgae, currently still experimental. The outcome of the legislative process is still uncertain, but it is nonetheless clear that the issue of the viability of production of non-crop based biofuels will be of key practical and policy relevance.

In line with the EU directives, Italy introduced the obligation for the gasoline and diesel suppliers (Obligated Subjects) to release for consumption a minimum quota of biofuels, to develop a supply chain, to increase their use, and to reduce the CO_2 released into the atmosphere. To fulfil these needs, however, Italy relies mostly on direct imports from outside the country or on the transformation of imported raw materials, particularly from Indonesia, thus contributing to the adverse effects in terms of risks of biodiversity loss and other environmental impacts of biofuel production overseas.

The set of relevant national policies lacks measures that, taking into account the latest technological developments in the sector, stimulate production and use of advanced biofuels in the country. Thus, despite the effort, biofuels-related incentive mechanisms put in place in Italy have proven unable to stimulate the shift from first-generation to second- and third-generation biofuels, favouring a stabilisation around the minimum quota of first-generation biofuels instead.

Against this background, we put forward for consideration the viability of a domestic *Brassica carinata*-derived biofuel production and supply chain. *Brassica carinata* (henceforth, also BC) is a non-food crop with agronomic features that make it particularly suitable for crop rotation with food plants, such as wheat, and can also be considered suitable for marginal and contaminated areas, as it has phytoremediation properties. Moreover, it is mostly unsuitable for rotation with other energy crops, as in this case it is exposed to diseases such as sclerotinia (Zegada-Lizarazu and Monti, 2011). These features allow to substantially mitigate concerns on the impact of its production on the rise of food prices and on land use change that have been so prominent in the biofuels debate. Therefore, *Brassica carinata* appears to be a promising candidate as a crop that could be used to stimulate local biofuel production in Italy, where there are two million hectares of wheat cultivations, provided it is also sustainable from an economic and environmental standpoint.

In light of the above, the objective of this study is to analyse the economic and environmental sustainability of biodiesel obtained from BC cultivated in crop rotation with wheat. The study evaluates the economic sustainability of the entire biodiesel production chain (considering the following phases: cultivation, oil extraction and oil refining), taking into account potential returns from the sale of biodiesel and its by-products, glycerine and expeller/meal. Yield and cost production data relate to five experimental fields of BC seeds multiplication in the provinces of Grosseto and Siena (Tuscany, Italy). To test the environmental sustainability of BC and its compliance with the RED requirements, we perform a Life Cycle Assessment (LCA) of the CO_2 emissions per energy content of biodiesel produced. More specifically, we estimate CO_2 emissions of BC-derived diesel production in terms of Kg_{co2}/Kg_{fuel} and in terms of gCO_{2eq}/MJ, making use of the Argonne National Laboratory's GREET (Greenhouse gasses, Regulated Emissions, and Energy use in Transportation) life-cycle model suite, and evaluate the CO_2 reductions when compared with the CO_2 emissions per energy content of mineral diesel production.

The paper is structured as follows. Section 2 outlines the motivation and related literature. Section 3 briefly illustrates the methodology used to determine the economic feasibility and environmental sustainability of BC-derived biodiesel production. Section 4 analyses the economic feasibility of the entire biodiesel value chain (from cultivation to the oil pump) and marketing chain. Section 5 evaluates CO_2 emissions for the whole production process. Section 6 discusses the results in light of the Italian economic and policy framework. Section 7 concludes.

2. Motivation and related literature

As mentioned in the introduction, biofuels have been identified as important contributors to the reduction of GHGs emissions. However, after an initial phase of euphoria and great expansion of their use, detailed analyses of their production highlighted ethical, political, and environmental issues, that have attracted significant policy attention. For instance, in 2008, the European Environment Agency (EEA) published the *Energy and Environment Report*, warning that the expansion of bioenergy production could cause adverse effects on the environment, compromising the conservation of biodiversity and water resources.

Adverse effects of biofuel production have, indeed, been underlined with respect to the problem of deforestation and indirect land use change (ILUC), particularly with regard to palm oil. This is because the largest palm oil producers include in their production chains the burning of peat forests or other types of deforestation, increasing the carbon debt (Fargione et al., 2008; Searchinger et al., 2008). During the last century, for instance, Indonesia lost at least 15.79 million hectares of forestland because of their conversion to palm oil production, becoming the third major GHGs emitter besides China and USA.

Moreover, since about 2005, biofuel-related food prices experienced phases of remarkable increase and appear to have stabilized in the past few years around a level higher than that pre-2005. Whether price increases can be causally attributed to the rise in biofuels production is still to some extent a contentious issue (compare, for instance, the conclusions by De Gorter et al., 2013; Hochman et al., 2012; To and Grafton, 2015), but the price trend is clear, as can be seen from Fig. 1.

These debates have triggered interdisciplinary research on the potential for alternative, non-food based biofuels (see, e.g., Carriquiry et al., 2011; Fazio and Monti, 2011; Stoeglehner and Narodoslawsky, 2009). Second generation feedstock include lignocellulosic biomass, non-food crops and bio-based waste raw materials. *Brassica carinata* is one such non-food crops (Cardone et al., 2003; Gasol et al., 2007). Most of the literature on the LCA and economic viability of biofuels production from the various feedstock moves from the assumption that land is used for the sole purpose of growing alternative raw materials for biofuels (see, e.g., (Del Gatto et al., 2015; Fiorentino et al., 2014; Sieverding et al., 2016). The potential for the development of biofuel production in

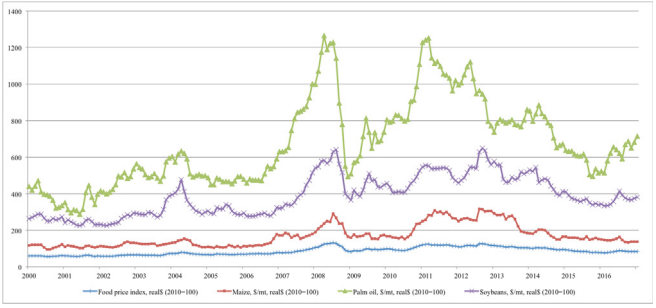

Fig. 1. Inflation-adjusted prices of maize, palm oil, soybeans and a food price index—2000–2016. Source: World Bank Global Economic Monitor Commodities.

a context of crop rotation has not been thoroughly explored (Zegada-Lizarazu and Monti, 2011).

Energy crops rotation, however, may be regarded as particularly interesting in presence of: current widespread use of lands for monoculture, interest in domestic production of biofuels in a policy context characterized by the progressive phase-out of first-generation biofuels, and concerns for land use change. All of these features recur in the Italian case.

The amount of biofuels released for consumption in Italy in 2016 was approximately 1.18 million tons. About 97% of it was made up of biodiesel. Sustainable biofuel accounted for 99.8% of the total. Domestic production was relatively limited. About 30% of biodiesel was generated in Italy, and only a small proportion (9.6%) was derived from raw material of national origin (GSE, 2018).

Most of the biodiesel is either directly imported or obtained from raw materials imported from outside Italy. The large majority of direct imports (about 90%) come from European countries. In 2016, Spain became the largest exporter of biofuels to Italy, produced with raw materials obtained mostly from Indonesia and to some extent, Argentina. The Netherlands, Austria and France follow, with biofuels originated from various sources, again including Indonesia. As for imports of raw materials, the main source was non-European, with Indonesia accounting for about 34% of the total (GSE, 2018).

The composition of Italian imports can be partly explained by a series of trade measures imposed by the EU to impede the import of bioethanol and biodiesel from outside the EU. In particular, in 2013, the EU imposed anti-dumping duties on biodiesel import from Argentina and Indonesia (on average 24.6% for Argentina and 18.9% in Indonesia). However, in September 2016 the EU General Court ruled that anti-dumping duties against Indonesian and Argentine biodiesel imports should be cancelled, and in January 2018 the EU Council has decided to withdraw the appeal against this ruling, again modifying the trade scenario, this time in a direction incompatible with the environmental concerns raised especially by Indonesian production.

These data suggest that in Italy there is ample scope for an increase in domestic production of energy-related raw materials and of biodiesel, and that such increase would have positive effects in terms of environmental impacts overseas. It should also be pointed out that in Italy there are two million hectares of wheat cultivations, which opens the way to the possibility of developing rotations with energy crops. We propose that, in this framework, BC could represent a sustainable alternative to palm oil and the associated ILUC problems overseas, while also mitigating concerns for land use change in Italy, given that BC can be cultivated in rotation with wheat (as well as on marginal or polluted land), and that it is a natural cleaner that also increases soil productivity. Our objective is thus to evaluate whether promoting the development of a BC-derived biodiesel production chain may contribute to sustain the Italian response to the increased EU policy orientation towards second-generation biofuels.

3. Methodology

3.1. Background: Brassica carinata's main features

BC is a natural alloploid of *Brassica Oleracea* and *Brassica Nigra*. Hybridization occurred thousands of years ago in Ethiopia, and the plant has been cultivated in the Horn of Africa because of its tolerance to drought and heat. BC has been farmed in Europe since the Bronze Age as a major crop and oilseed crop. It has been introduced in many countries all around the world from Australia to the US, from Europe (Spain and Italy) to Asia (Pakistan and India), and has been tested in Dakota, Montana, Florida, and Mississippi. BC is a promising oil feedstock for cultivation in coastal areas of central-southern Italy (Cardone et al., 2003).

BC is a good candidate for rotation with major crop plants, such as wheat, since it leaves moisture and soil nutrients quantitatively at least analogous to a fallow year. Also, in the past fifteen years, studies have highlighted the high potential of plants from the Brassicaceae family to phytoremediation (Anjum et al., 2012; Pane et al., 2012) and their high adaptability, pointing them out as natural candidates for *phytoextraction* and *phytostabilization* of contaminated lands when contaminants cannot be degraded. In particular, BC has shown a natural ability to absorb, accumulate and detoxify contaminants (Szczygłowska et al., 2011).

Brassicaceae are very hardy plants with reduced needs for technical and water resources. BC is an annual herb (30–280 cm), and its root system grows 40–50 cm thick. It produces up to 200 flowers; each cylindrical siliqua has 10–20 seeds, 2 mm long and 2–5 mg of weight. Seeds and harvest depend on some silique in every plant. BC seeds oil content ranges between 30 and 50% (erucic acid 42%, oleic 8%, linoleic 16%, linolenic 18%, eicosanoic 7%), the protein level is very high (>30%) and the fiber substance is small (<3%). In dry regions, it flowers and produces ripe seeds in 4 months from sowing; with adequate moisture, BC produces seeds in 6 months.

In the field, there is no strong evidence that BC could become a major invader, so that it is not listed in the US Federal noxious weed list. Moreover, BC provides multiple benefits as a bio fumigant, suppresses soil-borne diseases, pests, and insects, such as mycelium in potato diseases (Furlan et al., 2010).

3.2. Goal definition

The goal of the analysis is twofold. First, to study the economic feasibility of the entire biodiesel production chain (see Fig. 2), including cultivation, oil extraction, oil refining, and sale of biodiesel and its by-products, glycerine and expeller/meal (Carmody et al., 2001; Scragg, 2009). Second, to confirm the environmental sustainability of BC-derived biodiesel production. For this purpose, we perform a LCA estimating CO_2 emissions over the above-defined production chain on the basis of the Argonne National Laboratory's GREET (Greenhouse gasses, Regulated Emissions, and Energy use in Transportation) life-cycle model suite.

The economic viability assessment uses data for yields and production costs referred to the cultivation technique adopted in 2007/08 in five experimental fields of BC seeds multiplication. The fields were in the province of Grosseto and Siena (Tuscany, Italy) and each had an area of 1 ha. The cultivation technique included: the plowing, consisting of two rotary harrow passages; the fertilization, carried out in two phases (pre-sowing and coverage); the sowing; and, finally, the threshing.

The analysis takes into consideration exclusively the direct variable costs (of goods and services) incurred in the five multiplication fields. The price of land capital use, interests on loans and fixed assets depreciation are not taken into account because of the hypothesis under which the assessment is conducted, namely that BC is cultivated in crop rotation with wheat. The price of land

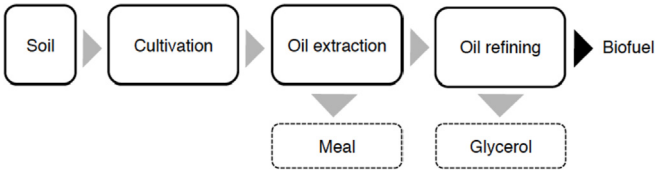

Fig. 2. Stylized biodiesel production chain.

capital use is therefore negligible, because the main use destination of the land is wheat production and BC production is considered only in the years in which the land should be left uncultivated. Other capital investments are also extremely limited because the standard equipment can be used. However, because of the small size of the BC seeds (1000 seeds weigh about 4.5 g), some changes were made to the technical means routinely used for the wheat cultivation in order to adapt it to BC cultivation.

As for the LCA assessment, given that *Brassica carinata* (BC) has no ILUC impact in the context we consider, our LCA considers only the CO_2 emissions per energy content of biodiesel produced. Since GREET does not offer a specific LCA for BC, we built a BC biodiesel production pathway in the GREET Fuel-cycle (or WTW) model covering the cultivation, oil extraction and oil refining. The path was made of the following processes available in the database: "Camelina farming", "Camelina to Camellia oil" and "Vegetable oil transesterification". We then modified the processes introducing as primary resources "BC seed", "BC meal", and "BC oil"; primary resource values were taken from (Sieverding et al., 2016).

To estimate CO_2 reductions, we compared our results with those of mineral diesel production, equal to 83.8 gCO_{2eq}/MJ, through the formula:

$$\begin{aligned}\text{SAVING} = &(\text{Total emission from mineral diesel production}\\ &-\text{Total emissions from BC derived biodiesel production})\\ &\times/\text{Total emission from mineral diesel production}.\end{aligned}$$

4. Results

4.1. Economic feasibility

In the following, we report the analysis conducted for each phase of the process: cultivation, oil extraction, oil refining, and sale of biodiesel and its by-products, glycerine and expeller/meal.

4.1.1. BC cultivation

The manufacturer reports that, given the small size of BC seeds, a good preparation of the seedbed was necessary to ensure proper deposition and uniform emergence. The soil was prepared with two passes of a disk harrow. The first pass allowed stimulating the germination of the weed seeds that were subsequently devitalized with the second pass of a harrow, made shortly before sowing. The cost per hectare of the treatments with a harrow was estimated at an average of 88 €/ha.

Given the excellent resistance of the plant, the manufacturer did not consider necessary to use herbicides, given that no significant gains in production were expected. Nonetheless, on a large-scale cultivation, it is recommended to use Trifluralin, a pre-emergence herbicide to be buried inter/on land ready for planting, which has a cost of 38 €/ha (product cost 24 €/ha + weeding cost 14 €/ha). The fertilization was divided into two phases: the first being pre-sowing with an NP fertilizer, followed by a coverage nitrogen fertilization (40–60 units). Costs incurred for fertilization were found to be 20 €/ha, and fertilizers used cost 92 €/ha.

The sowing was carried out with striped Pneumatic seed drill Accord DL, suitably adjusted to the small size of the seeds (seed depth 2–3 cm), at a cost of 74 €/ha. The collection was done with the combine in the first weeks of July when the grain moisture was around 9% and not more than 11%. The costs of threshing amounted to 101 €/ha.

The data available on the yields obtained in the five areas revealed an average production of 2 tons per hectare with minimum and maximum values of 1.6 and 2.6 tons respectively. These oscillations are broad, but the extremes are not particularly significant given the small size of the cultivated area (without using herbicides) and the fact that the year under review was the first in which the farm undertook BC cultivation (Table 1). The results are in line with the literature reporting that plant seeds have a yield that ranges between 1.5 and 2.8 t/ha, according to the soil and climate characteristics (Raccuia et al., 2013; Seepaul et al., 2015). All data used henceforth are referred to this average yield (2 tons).

4.1.2. Oil extraction

The crude oil extraction from the seeds is an essential step in the process of biodiesel production, as well as the separation between fat and protein components of the seeds subjected to the process.

The extraction techniques can be both mechanical (normally cold-pressure) and chemical (solvent, usually hexane). As an indication, the mechanical extraction is carried out on seeds containing fatty matter in quantities higher than 20%, and allows reaching up to 10–15% of residue; for lower values, chemical extraction is used. Both types of extraction mainly produce raw oil but differ in the kind of by-product generated. The mechanical extraction generates the expeller protein or meal, while chemical extraction produces flour. Because it has higher oil and protein content, the former is relatively more valuable for use with livestock (beef, swine, dairy and aquaculture).

The mass balance of the entire extraction process provides information about the product and by-product percentages that we get from this phase. From the processing of one ton of seeds with 42% oil yield, we get 420 kg of crude oil and 580 kg of expeller/meal. This is in line with previous studies reporting that BC seeds have a percentage of oil content varying from 32% to 49% for the Italian central and northern regions, and from 34% to 40% for the southern regions (Cardone et al., 2003). The high concentration of erucic acid makes the BC oil subject to increasing demands by industry especially for processing of nylon and plastic, as a lubricant for high-performance motors and as a component in the production of mixtures of fungicides insoluble in water. The increased use of BC derives from the industry need to create products suitable to meet increasingly demanding targets of less polluting products.

Data about the extraction of crude oil were derived from a previous collaboration between the chosen refinery and the Province of Siena (IT), which implemented a short biodiesel chain from sunflower in 2008. Oil extraction costs amounted to 47.72 €/ton.

4.1.3. Oil refining

Refining is the stage of conversion of the vegetable oil into the finished product. To use the vegetable oil as a fuel in diesel engines, foreign substances (proteins, rubbers, resins, phosphatides, ketones, aldehydes) have to be removed. The glycerine present in crude oil makes the product more viscous than the fuel oil, so that it could cause damage to pumps and injectors if used directly in a conventional engine. The solution is to reduce its viscosity. Through a chemical process called transesterification, the glycerol is replaced with another substance (methyl alcohol) to obtain the methyl ester or biodiesel. After this process, it is possible to use biofuel in a standard engine. The ratio between refined oil and biodiesel is 1:0.98 because it is necessary to subtract the crude oil losses during the refining process, accounting for about 2% of the

Table 1
Yields of *Brassica carinata*.

Yields	I	II	III	IV	V	AVG
Grain yield (t/ha)	1.6	1.7	2	2.3	2.6	2

total. The simplified mass balance of the whole process is the following: 1 ton of oil refined methanol +100 kg BC crude oil = 0.98 ton of biodiesel +100 kg glycerol. The amount of biodiesel by-product, or glycerine, is equal to 10% of its weight. Table 2 reports refining, transesterification and storage costs[1]; these costs take into account the purchase of methanol, combined with oil in a percentage of 10%, to get the fuel.

Considering the above-illustrated cost components, it is now possible to provide an estimate of the production cost of 1 ton of BC-derived biodiesel, by applying the relevant proportions (Table 3).

4.1.4. Sale of biodiesel and co-products

To assess the economic sustainability of BC-derived biodiesel, it is necessary to compare overall production costs to the total revenues that can be obtained from the production chain. This is more straightforward for co-products (expeller/meal and glycerine) than for the biodiesel itself, as in Italy, there currently is no market for biodiesel, and therefore no directly observable selling price.

To evaluate overall economic viability, it is therefore necessary to identify potential buyers of second-generation biodiesel and products that may be competitors on the market, using the prices of the latter as a proxy for potential revenues. Potential buyers are those subjects that have not reached the required number of certificates of release (see below, section 6). Competing products are other available biofuels. Which products should be considered substitutable with BC-derived biodiesel, and therefore competing with it, depends in part on the EU and Italian policy framework. At present, BC-derived biodiesel competes with first-generation biofuels. To the extent that the current trend towards the progressive reduction of the role of first-generation biodiesel continues, however, the real competitive constraint on BC-derived biodiesel will be exerted by other second-generation biofuels and third-generation biofuels, as first-generation biofuels will not fulfil the necessary environmental requirements. In this case, it would therefore be necessary to refer to the (higher) price of the second- and third-generation biofuels to evaluate the economic viability of BC-derived biodiesel.

In what follows, we provide a conservative estimate of the overall revenues obtainable from the sale of 1 ton of biofuel and co-products, providing data only for the lower bound values of each revenue source.

To obtain an estimate of the average selling price of first-generation biodiesel, it is possible to refer to the data on the value and quantity of biofuel imports to Italy in 2014, provided by the US Foreign Agricultural Service GAIN Report (USDA Foreign Agricultural Service, 2015), which uses data from the Global Trade Atlas. Dividing the yearly USD value of imports by the quantity imported and converting the resulting unit price in euros, a price of about 770 €/ton is obtained. As for second-generation biofuels, since the market is obviously even less developed than that for biofuels in general, price proxies are hard to identify. However, prices are expected to be higher than those of first-generation biofuels in case the policy context will further favour the phase-out of the latter.

Table 2
Main costs of the refining process.

	Unit cost (€/T)
Oil refining	70.00
Transesterification	100.00
Storage	10.00

Table 3
Cost components of 1 ton of BC-derived biodiesel.

Cost component	Unit cost (€/t)
Cultivation	501.70
Oil extraction	115.94
Oil refining	71.43
Transesterification	102.04
Storage	10.20
Total	801.31

The first co-product of biodiesel production that we considered is meal. To get an estimate of the price per ton that can be obtained from Carinata meal, we refer to the latest annual data point available (2015/16), provided by FAO (2017), which gives a price of 232 USD/ton for rapeseed meals. This estimate can be considered rather conservative, as it represents the lowest annual data point since 2010/11. Converting the price per ton to euros at the average official annual exchange rate USD/EUR calculated over the period July 2015–June 2016 and multiplying it by the amount of meal obtained as the co-product of 1 ton of biodiesel, we obtain a revenue from this co-product of about 294.7 €/ton of biodiesel.

The second co-product considered is glycerine, the product of hydrolysis or transesterification of vegetable oils that the law configures as simple fodder. We take, again, a conservative approach by considering the average spot price observed on the European market for *crude* glycerine of the non-GMO quality in the last two weeks of 2017 (Oleoline, 2017). We therefore not consider at this stage the possibility to sell glycerol for specific high-value uses, such as niche and highly profitable products (in the areas of cosmetics and pharmaceuticals). Converting the average price per ton to euros as before and multiplying by the amount of glycerol obtained as the co-product of 1 ton of biodiesel, we obtain a revenue from this co-product of about 41.8€ per ton of biodiesel. Table 4 summarizes the total revenues associated to the production of 1 ton of BC-derived biodiesel.

As can be seen from the above table, the economic viability of the BC production chain is confirmed, even adopting conservative assumptions.

4.2. Environmental impact

Evaluation of the environmental sustainability of biodiesel derived from BC was performed by using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Life-Cycle Assessment Model from The Argonne National Laboratory's Systems Assessment Group (v. 2016). For each fuel system, the software GREET separately calculates the following:

Table 4
Revenues from 1 ton of BC-derived biodiesel.

Product	Revenue per ton of biodiesel (€/t)
biodiesel	769.2
Carinata meal	294.7
Crude glicerine	41.8
Total revenue	**1105.7**

[1] The reported cost estimates are based on interviews conducted in local refineries. While costs may be rather volatile, the estimates can be considered an acceptable approximation as 'official' or standard costs of transesterification are not available.

- "consumption of total resources (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal, natural gas and water;
- emissions of CO_2-equivalent greenhouse gases - primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O);
- emissions of seven criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), particulate matter with size smaller than 10 μm (PM_{10}), particulate matter with size smaller than 2.5 μm ($PM_{2.5}$), black carbon (BC), and sulphur oxides (SOx)" (https://greet.es.anl.gov/).

GREET is a life-cycle assessment model of a fuel production pathway. It evaluates inputs, outputs and environmental impacts of a product system throughout its lifecycle. Once defined the product, in our case BC, and the system boundary, in our analysis from well-to-tank, GREET determines the LCA. In this case the biodiesel production pathway was distinguished into three phases: Production, Pressing and Transesterification. We referred to Life-Cycle Analysis of Alternative Aviation Fuels in GREET (Elgowainy et al., 2013). In production or cultivation of BC we considered fertilizers and diesel for non-road applications and GREET determined 207.11 Kg of CO_2 total emissions (−0.19 kg CO_2 Biogenic). Transformation of BC into Brassica oil and Brassica meal, that involved natural gas, diesel for non-road applications, N-Hexane and electricity consumption, determined 470.78 Kg of CO_2 total emissions (−0.44 kg CO_2 Biogenic). Finally transesterification that transforms Brassica oil into Biodiesel and Glycerine, by using methanol, water process, natural gas and electricity, determined 776.18 Kg of CO_2 total emissions (−0.43 kg CO_2 Biogenic) per 1 ton of biodiesel.

To estimate the CO_2 reductions, we compared our results with those of mineral diesel production (3.2 $KgCO_2/Kg_{fuel}$, equal to 83.8 gCO_{2eq}/MJ, MISE and MPAA, 2012, p. 32), through the formula:

$$\begin{aligned}\text{SAVING} = &(\text{Total emissions from mineral diesel production}\\ &-\text{Total emissions from BC derived biodiesel production})\\ &\times /\text{Total emissions from mineral diesel production}.\end{aligned}$$

Summarizing, the GREET LCA Model for production of biodiesel from BC determines a total emission of 1.454 $KgCO_2/Kg_{fuel}$ (38 gCO_{2eq}/MJ), when using fertilizers in the cultivation process. The estimated CO_2 total emission is in accordance with the values estimated by Sieverding et al. (2016, Figure 3) that highlights that BC had GHGs emissions lesser than 1.5 Kg_{co2}/Kg_{fuel} and performed better than sunflower and canola. Finally, CO_2 reductions of biodiesel from BC with respect to mineral diesel production were estimated to be greater than 50%.

5. Discussion and policy implications

The analysis presented in the previous sections has shown that a BC-derived biofuel production chain in crop rotation with wheat (and eventually other crops) is economically viable, and environmentally sustainable. In this section, we discuss these results within the broader Italian economic and policy context.

Italian environmental policies in the transport sector comply with the relevant European Directives. Two main policy instruments have historically been adopted in Italy: a tax/excise reduction and an obligation to make a quota of biofuels available for consumption (Finco and Padella, 2013). The first has been adopted between 1995 and 2010, but it has subsequently given way to a system of bio-certificates linked to quota obligations. Subjects releasing petrol and diesel fuels for consumption (liable/obligated parties) are required to release for consumption also a minimum quota of biofuels, calculated on the basis of the total calorific value of petrol and diesel supplied in the previous year. To monitor the quantity of biofuels effectively released in the Italian market, certificates known as "*Certificati di Immissione in Consumo* (CIC)" are attributed to liable/obligated parties for each 10 gal derived from biofuels released for consumption (Decree No. 110 of April 29, 2008). The same legislation also provides for the possibility to trade certificates among the responsible parties on dedicated platforms. Given that the law foresees administrative fines for failure to meet the quota obligation and obtain the required number of certificates, the value of traded certificates of course depends on the amount of the fines. The law distinguishes the amount of the penalty based on the different weight percentage of release for consumption of the missing certificates. Penalties range from 600 to 900 € per certificate (10 gcal).

As argued by Schimmenti et al. (2012), these tools have so far proved to be limited and uncertain, preventing the development of domestic biodiesel production chains, together with the stiff competition from imports, and contributing instead to the Italian energy dependence regarding biodiesel and vegetable oils.

In spite of the overall limitations of Italian biofuels policy, the quota system should nonetheless be considered susceptible to contribute to the sustainability of the BC-derived biodiesel production chain. Indeed, by releasing for consumption biodiesel in Italy, BC-derived biofuel producers could obtain bio-certificates tradable on the dedicated platforms. As a first rough approximation, their (implicit) value can be estimated by reference to the lowest fine that could be avoided by their purchase (600€). Considering the total calorific power of 1 ton of BC-derived biodiesel (Cardone et al., 2003), release into consumption of 1 ton of biodiesel corresponds to 0.86 certificates. This implies, at the mentioned implicit value, and taking into account costs of certification amounting to approximately 10% of the certificate's value, to additional revenues of about 464€.

As elsewhere, also in Italy a combination of past incentives from the Common Agricultural Policy (CAP), farmers' beliefs that monoculture is still the most profitable option, and unfamiliarity with the management requirements of crop rotation, has so far prevented the diffusion of the cultivation of non-food energy crops in rotation with food crops. Our analysis shows that the resistance may eventually be spontaneously overcome, because domestic production of biofuel from BC is economically viable and environmentally sustainable.

The major obstacle to the development of local production remains, of course, the competition from cheap imports of raw materials suitable for the production of first generation biodiesel, and particularly of palm oil. Palm oil prices have shown a declining trend since the peak experienced in 2010, when the price reached 1240 $/metric ton.[2] Moreover, final import price has been kept low by the evolution of Indonesia's export tax policies. Indeed, the progressive *ad valorem* export tax on crude palm oil introduced in 1997 was first transformed into a flat tax of 3 $/ton and now completely eliminated. As of February 2018, the price of crude palm oil from Indonesia was 665 $/metric ton or 486 €/ton. Considering the current anti-dumping tax of between about 8% and 23%, overall crude oil price was comprised in a range of about 525–598 €/ton.

Local production of BC oil as an input to biodiesel production does not fare badly with respect to these price estimates. As can be seen from the first two rows of Table 3, the cost of locally produced BC oil can be estimated to be around 618 €/ton. Considering that production costs may decrease with cultivation on a larger scale that the experimental scale considered in this study, and

[2] The price indicated is the crude palm oil price FOB Belawan/Dumai. See http://www.palmoilanalytics.com/price/15, last accessed on March 8th, 2018.

considering shipping costs for Indonesian palm oil, there seems to be space for local production at current prices. However, as explained in section 2, antidumping duties are about to be lifted, imposing further constraints on the incentives to local production of BC oil. Thus, whether it will be possible to address the disastrous environmental concerns raised by palm oil-derived biofuel through domestically produced BC production will depend on whether the ban on the use of palm oil foreseen by the proposed RED II will be confirmed, and on the nature of biofuel-related policies in Italy.

The adoption of policies meant to actively support the development of a BC-derived biodiesel production chain may find an economic justification in the range of externalities and positive economic effects that it would generate. Promoting an Italian second generation biofuels industry-agriculture system will yield to a win-win situation implying the following positive economic effects and externalities:

- a reduction of the use of first-generation biofuels production and consumption regarded as a source of land grab, *indirect land-use change* (ILUC), rising food prices and even climate change;
- a reduction of imports of first generation biofuel from soy and palm oil incorporated into transportation fuels;
- the reinforcement of the supply chain from land to pump by creating positive revenue for farmers and bio-refinery owners;
- if national oil companies were involved in the process, instead of importing first-generation biodiesel, some of the refineries closed because of overproduction could be converted in bio-refineries and offer new employment, in a country where the unemployment rate is at 10.8% (as of December 2017);
- a stimulus to the development of a local biofuels market;
- finally, in so far as BC production occurs in marginal lands and/or land presently not cultivated because too polluted, also an improvement in the productive utilization of land.

A range of policy measures may be adopted to promote these desirable developments. One option of high practical relevance, though perhaps less theoretical, would be for Italian policy makers to exercise a form of moral suasion towards big players of the energy sector (i.e. ENI) to invest in the development of a domestic production and supply chain. Since 2016, for instance, ENI and Marina Militare Italiana have had a supply contract of biodiesel from palm oil processed in the bio-refinery Irom (Porto Marghera, Venice). Also in view of the more demanding targets currently under discussion at the European level, it would desirable that supply was converted to second-generation biodiesel. Other measures may include awareness-increasing information campaigns towards farmers, which could provide them with the necessary information to consider BC production in crop rotation with wheat or other crops, and using public procurement as a tool to stabilize demand for second- and third-generation biofuels. As regards the last measure, it is worth noting that Italy has been the first country in Europe to impose to public administrations, which account for about 17% of GDP, an obligation to consider the environmental impact of the goods and services they purchase over their entire lifecycle (New Public Procurement Code, Legislative Decree 56/2017). Thus, although some uncertainties in the application of the new rules have so far hampered their full effectiveness, the legal framework appears already set to favour public procurement of second- and third-generation biodiesel.

6. Conclusions

This paper investigated the economic feasibility and environmental sustainability of producing second-generation biofuel in Italy from *Brassica carinata,* a non-edible flowering plant of the *Brassicaceae* family, in a context of rotation with wheat (and eventually other crops). The economic analysis used yield and cost data from 5 experimental fields in Tuscany, as well as relevant data from the literature to evaluate the economic sustainability of the entire biodiesel production chain (considering the following phases: cultivation, oil extraction and oil refining), taking into account potential returns from the sale of biodiesel and its by-products, glycerine and expeller/meal. As for the environmental sustainability analysis, it was performed with the Argonne National Laboratory's GREET (Greenhouse gasses, Regulated Emissions, and Energy use in Transportation) life cycle model, suitably adjusted so as to apply it to the BC case.

Focusing on a context of crop rotation allowed us to consider a use case that is highly relevant to a country where there are more than two million hectares of wheat cultivations, and a very high degree of dependence from foreign sources as far as energy crops, vegetable oils and biofuel production are concerned. We conclude that, in this framework, BC could represent a sustainable domestically produced alternative to palm oil, thus contributing to mitigate ILUC problems overseas, while also addressing concerns for land use change in Italy. Moreover, the development of a BC-derived biodiesel production chain may trigger a range of positive economic effects and externalities, contributing to sustain the Italian response to the increased EU policy orientation towards second-generation biofuels.

While the evidence we provide on the economic viability of BC-derived biodiesel production suggests that a progressive shift towards BC crop rotation may spontaneously occur, the high variance in yields reported in the literature, as well as the existence of externalities linked to the development of a BC-related production chain suggest that some form of policy intervention may be necessary to ignite this win-win situation. Current Italian policy for biofuels foresees only the double counting and tradable biocertificates linked to a quota system and lacks an efficient system of integration between the industrial and the agricultural sector. To meet the EU Energy and Climate targets, possibly ever more demanding in light of the update of the RED, a wider and more effective set of policy tools may be required.

Declarations of interest

None.

Acknowledgements and funding

The authors wish to thank two anonymous referees for providing valuable comments on a previous version of this article.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Anjum, N.A., Ahmad, I., Pereira, M.E., Duarte, A.C., Umar, S., Khan, N.A., 2012. The Plant Family Brassicaceae: Contribution towards Phytoremediation. Springer Science & Business Media.

Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Senatore, A., Seggiani, M., Vitolo, S., 2003. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass Bioenergy 25, 623–636. https://doi.org/10.1016/S0961-9534(03)00058-8.

Carmody, P., Carr, H., Morcom, A., Walton, G., 2001. Alternative Oilseeds R&D for Biodiesel Production.

Carriquiry, M.A., Du, X., Timilsina, G.R., 2011. Second generation biofuels: economics and policies. Energy Pol. 39, 4222–4234. https://doi.org/10.1016/j.enpol.2011.04.036.

De Gorter, H., Drabik, D., Just, D.R., 2013. How biofuels policies affect the level of grains and oilseed prices: theory, models and evidence. Glob. Food Sec. https://

doi.org/10.1016/j.gfs.2013.04.005.
Del Gatto, A., Melilli, M.G., Raccuia, S.A., Pieri, S., Mangoni, L., Pacifico, D., Signor, M., Duca, D., Foppa Pedretti, E., Mengarelli, C., 2015. A comparative study of oilseed crops (Brassica napus L. subsp. oleifera and *Brassica carinata* A. Braun) in the biodiesel production chain and their adaptability to different Italian areas. Ind. Crop. Prod. 75, 98–107. https://doi.org/10.1016/j.indcrop.2015.04.029.
Elgowainy, A., Han, J., et al., 2013. Life-cycle analysis of alternative aviation fuels in GREET. J. Chem. Inf. Model. 53, 1689–1699. https://doi.org/10.1017/CBO9781107415324.004.
FAO, 2017. Oilseeds, Oils and Meals, Monthly Price and Policy Update.
Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. Science 319 (80), 1235–1238. https://doi.org/10.1126/science.1152747.
Fazio, S., Monti, A., 2011. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass Bioenergy 35, 4868–4878. https://doi.org/10.1016/j.biombioe.2011.10.014.
Finco, A., Padella, M., 2013. Biofuel policy in EU and Italy. In: Biofuels Economics and Policy. Agricultural and Environmental Sustainability. Franco Angeli.
Fiorentino, G., Ripa, M., Mellino, S., Fahd, S., Ulgiati, S., 2014. Life cycle assessment of *Brassica carinata* biomass conversion to bioenergy and platform chemicals. J. Clean. Prod. 66, 174–187. https://doi.org/10.1016/j.jclepro.2013.11.043.
Furlan, L., Bonetto, C., Finotto, A., Lazzeri, L., Malaguti, L., Patalano, G., Parker, W., 2010. The efficacy of biofumigant meals and plants to control wireworm populations. Ind. Crop. Prod. 31, 245–254.
Gasol, C.M., Gabarrell, X., Anton, A., Rigola, M., Carrasco, J., Ciria, P., Solano, M.L., Rieradevall, J., 2007. Life cycle assessment of a *Brassica carinata* bioenergy cropping system in southern Europe. Biomass Bioenergy 31, 543–555. https://doi.org/10.1016/j.biombioe.2007.01.026.
GSE, 2018. Rapporto Statistico. Energia da Fonti Rinnovabili - Anno 2016. https://doi.org/https://doi.org/10.1017/CBO9781107415324.004.
Harris, Z.M., Spake, R., Taylor, G., 2015. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioenergy 82, 27–39. https://doi.org/10.1016/j.biombioe.2015.05.008.
Hochman, G., Kaplan, S., Rajagopal, D., Zilberman, D., 2012. Biofuel and food-commodity prices. Agriculture 2, 272–281. https://doi.org/10.3390/agriculture2030272.
MISE, MPAA, 2012. Decreto interministeriale 23 gennaio 2012-Certificazione nazionale della sostenibilità dei biocarburanti e dei bioliquidi.
Oleoline, 2017. Crude Glycerine Market Report n.119.
Pane, C., Villecco, D., Pentangelo, A., Lahoz, E., Zaccardelli, M., 2012. Integration of soil solarization with *Brassica carinata* seed meals amendment in a greenhouse lettuce production system. Acta Agric. Scand. Sect. B Soil Plant Sci. 22, 291–299.
Raccuia, S.A., Melilli, M.G., Del Gatto, A., Pieri, S., Mangoni, L., Signor, M., Foppa Pedretti, E., Toscano, G., Mengarelli, C., Duca, D., 2013. Morphological, productive and energetic characterization of Brassica carinata in central, North and South areas of Italy. Acta Hortic 1005, 419–426.
Schimmenti, E., Borsellino, V., Galati, A., 2012. Recenti sviluppi del mercato comunitario e italiano del biodiesel. Primi risultati di un'indagine esplorativa in Italia. Econ. Dirit. Agroaliment. 17, 193–209.
Scragg, A., 2009. Biodiesel. Production, Application and Development. Cambridge University Press, Cambridge.
Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.H., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319 (80), 1238–1240. https://doi.org/10.1126/science.1151861.
Seepaul, R., Bliss, C., Wright, D., Marois, J., Leon, R., Dufault, N., George, S., Olson, M., 2015. Carinata, the Jet Fuel Cover Crop. Production Manual for the Southeastern United States.
Sieverding, H.L., Zhao, X., Wei, L., Stone, J.J., 2016. Life-cycle assessment of oilseeds for biojet production using localized cold-press extraction. J. Environ. Qual. 45 (967). https://doi.org/10.2134/jeq2015.06.0313.
Stoeglehner, G., Narodoslawsky, M., 2009. How sustainable are biofuels? Answers and further questions arising from an ecological footprint perspective. Bioresour. Technol. 100, 3825–3830. https://doi.org/10.1016/j.biortech.2009.01.059.
Szczygłowska, M., Piekarska, A., Konieczka, P., Namieśnik, J., 2011. Use of Brassica plants in the phytoremediation and biofumigation processes. Int. J. Mol. Sci. 12, 7760–7771. https://doi.org/10.3390/ijms12117760.
To, H., Grafton, R.Q., 2015. Oil prices, biofuels production and food security: past trends and future challenges. Food Secur. 7, 323–336. https://doi.org/10.1007/s12571-015-0438-9.
USDA Foreign Agricultural Service, 2015. GAIN Report "Italy: Biofuels Overview – December 2015 Update" n. IT15104.
Zegada-Lizarazu, W., Monti, A., 2011. Energy crops in rotation. a review. Biomass Bioenergy. https://doi.org/10.1016/j.biombioe.2010.08.001.